Experimental Assessment of Strain Gradient Plasticity Theories

M.M. Barney[1,2], G.H Campbell[1], J.S. Stölken[1], R. Spolenak[3], N. Tamura[2], R.O. Ritchie[2]
[1] Lawrence Livermore National Laboratory, University of California, Berkeley, California 94720, USA
[2] Lawrence Berkeley National Laboratory, University of California, Livermore California, 94551, USA
[3] Max-Planck-Institut für Metallforschung, Heisenbergstr. 3, D - 70569 Stuttgart, Germany

INTRODUCTION

The LLNL Multiscale Material Modeling Project is involved in predicting the quasi-static deformation of polycrystals using a length-scale bridging approach. This approach is based on simulations at and feedback between the atomistic, micro, meso, and continuum length scales. Conventional continuum models exhibit deficiencies in the mesoscale region, and must be modified to accurately model plastic deformation at this size scale. Different approaches designed to modify the continuum theory, known as strain gradient plasticity theories, have been developed recently and need to be explored experimentally.

Continuum models fail in the mesoscale region by not capturing the 'size effect'. This effect is seen experimentally as an increase in flow stress during deformation when strain gradients are large. This commonly occurs at small size scales or when inhomogeneties are present. For example, Fleck et.al.[1] showed that when loaded in torsion, a wire displays greater strength for smaller radii. This type of effect has been observed in other systems; including bending[2], indentation hardness[3], and particle-hardened alloys[4]. Because strain gradients are large under these conditions, they must be accounted for in a non-local theory to accurately reflect material response. The present authors are currently evaluating two distinct classes of non-local models. A key difference between the two models considered here is the nature of the assumed boundary conditions at material interfaces under simple shear. Fleck, Hutchinson, and Shu (FHS)[5,6] have developed one approach that considers strain gradients as internal degrees of freedom, which require higher order stresses and an additional boundary condition. Acharya and Bassani[7] have developed an alternative approach in which a strain gradient term is included in the hardening function. This method does not introduce higher order stresses or additional boundary conditions. Although this approach is simpler overall, the higher order (FHS) theory may be more predictive, because the additional boundary condition in this theory allows for the presence of a boundary layer. Specifically, Fleck and Hutchinson[6] determined theoretically that near an interface between dissimilar materials loaded under remote simple shear, a region of extra lattice rotation (called a boundary layer) should be present. Since boundary layers are not allowed in Acharya and Bassani's approach, detecting the presence of these layers at interfaces will supply critical information in the continued development of strain gradient plasticity theories. The presence of a boundary layer, however, has not yet been definitively determined. Although previous experimental work on metal-metal bicrystals by Sun et.al[9] suggests the presence of a boundary layer, the data are difficult to interpret due to the movement of the grain boundary. Therefore, microdiffraction experiments performed at metal-ceramic interfaces are proposed to determine lattice rotation information, which will help determine the validity of these two strain gradient plasticity theories without the complication of grain boundary movement.

EXPERIMENTAL PROCEDURE

The deformation behavior near an interface is being investigated with samples composed of 50 μm thick aluminum foils sandwiched between sapphire rods that are deformed using asymmetric four-point bending to produce a uniform shear stress state. In order to detect the presence of a boundary layer in the aluminum near the sapphire after shearing, the lattice rotations need to be measured from the center of the aluminum layer to an interface in one-micron steps. We are using Laue microdiffraction at the Advance Light Source[10] for this investigation. Recent experiments performed at the ALS have generated usable Laue patterns that have been indexed using software available at the beamline. Two separate samples were scanned; one in the as bonded condition with no deformation, the other after being sheared with 20% deformation. By using a laboratory reference orientation, the diffraction patterns from these two samples can be used to generate a map of the projected in-plane orientations of the grains.

RESULTS

The orientation map for each of the samples is shown below. The scale on the side is degrees of lattice rotation with respect to the laboratory reference orientation.

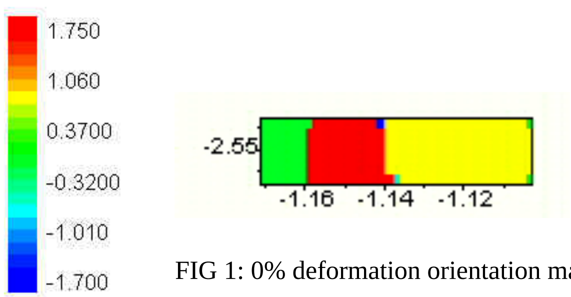

FIG 1: 0% deformation orientation map

The orientation map for the unstrained sample shown above shows the presence of two aluminum grains (middle and right blocks) in between two sapphire sections (on left). The total section is 60 µm across and 10 µm high. The orientation map below shows a sample with 20% shear deformation. The total section is 80 µm across and 10 µm high. Two different interpretations of this map are possible. Initially, it appeared that there were three grains of aluminum (blue, yellow, green) present between two sapphire sections (green sections on the edges), as well as a boundary layer (orange stripe on left hand side) of extra lattice rotation at only one interface. Having a boundary layer at one interface, but not the other, is difficult to explain theoretically. Neither of the solid mechanics theories we are considering predicts this behavior, nor does the extensive, well-established work on boundary layer theory in fluid mechanics. Additionally, however, it is possible that the small section scanned (80 µm by 10 µm) contained only one grain prior to deformation, and that all the features seen are from dislocation cell formation during the mechanical test (i.e.: no boundary layer formation). This seems likely, since the total (not projected) angles between what appear to be three different grains and a boundary layer are small (<10°).

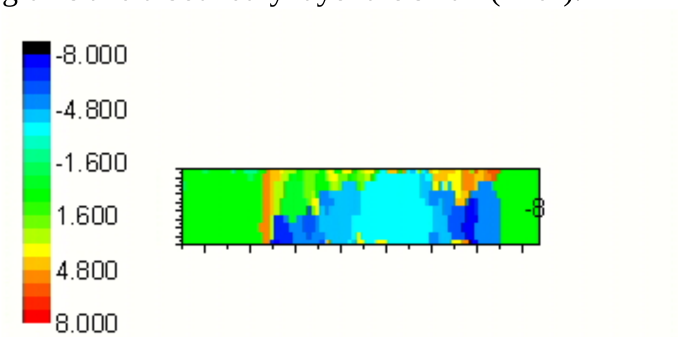

FIG 2: 20% deformation orientation map

To sort out the exact interpretation of this result, it is critical to obtain an orientation map of deformed samples prior to undergoing shear deformation. Specifically, this can be done by first scanning the sample with the X-ray beam, shearing it, and then scanning the same area again to see how the grains evolve. In this way, we obtain a 'before' and 'after' snapshot of the grain morphology and structure, making a definitive interpretation possible as to what is a grain, dislocation cell, recrystallized grain, or boundary layer in the final orientation map. These scans have been performed and are currently being analyzed. Confirming or refuting the presence of this boundary layer is the primary result of the experimental program. If the boundary layer is present, its characterization will be critical in providing parameters for the FHS model. Continued improvement of the model will be facilitated by further experimental results generated by continued investigations. The cyclic feedback of information between the experiments and the modeling has proven to be successful in other parts of the Multiscale Material Modeling Project.

ACKNOWLEDGEMENTS

The authors would like to thank Andrew Mei and Alexander Ziegler for sample preparation help, and both the MRI and SEGRF fellowship at LLNL for the funding awarded to M.M. Barney.

REFERENCES

1) N. A. Fleck, G. M. Muller, M. F. Ashby, and J. W. Hutchinson, Acta Metall. Mater. 42, 475 (1993).
2) J. S. Stölken and A. G. Evans, Acta. Mater. 46, 5109 (1998).
3) N. A. Stelmashenko, M. G. Walls, L. M. Brown, and Y. V. Milman, in Mechanical Properties and Deformation Behavior of Materials Having Ultra-Fine Microstructures, edited by M. Nastasi, D. M. Parkin, and H. Gleiter. (NATO ASI Series E 233, 1993) pp. 605-610.
4) D. J. Lloyd, Int. Mater. Rev. 39, 1 (1994).
5) J.Y. Shu and N.A. Fleck, J. Mech. Phys. Solids 47(2), 297 (1999).
6) N. A. Fleck and J. W. Hutchinson, J. Mech. Phys. Solids 41, 1825 (1993).
7) A. Acharya and J. Bassani, in Micromechanics of Plasticity and Damage of Multiphase Materials, IUTAM Symposium, Paris. Aug. 29 - Sept 1, 1995.
9) S. Sun, B.L. Adams, C. Shet, S. Saigal, and W. King, Scripta Met. 39, 501 (1994).
10) A.A.MacDowell, R.S.Celestre, N.Tamura, R.Spolenak, B.C. Valek, W.L.Brown, J.C.Bravman, H.A.Padmore, B.W.Batterman & J.R.Patel, Nuclear Instruments and Methods in Physics Research A 467-468, 936 (2001).

This work was supported under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract No. W- 7405-Eng-48

Principal investigator: Robert Ritchie, Ernest Orlando Lawrence Berkeley National Laboratory. Email: RORitchie@lbl.gov. Telephone: 510-486-5798.